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Research of a dual-frequency power supply system for induction crucible furnaces for melting ferrous and non-ferrous metals

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Abstract. The article describes the power supply system of induction furnace based on a semiconductor converter, in which it is possible to work simultaneously in the exciting mode of low-frequency currents and frequencies three times higher when switching the compensation circuit of the furnace inductor at different stages of metal melting. Calculations of electromagnetic processes have shown the advisability of operating the power supply system in the mode of tripling the current frequency at the stage of heating and melting of the metal, but in the mode of low frequency - at the stage of technological processing of the melt. The ratio between the parameters of the furnace power supply in various operating modes are established.

1. Introduction

Induction melting of metals at medium frequencies is widely used in many industries. The high efficiency of induction crucible furnaces is achieved by the optimal choice of design parameters, operating frequency and specific power, which helps to reduce the energy consumption of molten metal per ton. When melting ferrous and non-ferrous metals in induction furnaces, it is necessary to solve a number of technological problems associated with the implementation of metallurgical processes. During technological processes of alloying or carburization, it is advisable to actively mix the melt, however, the electromagnetic field force decreases with increasing frequency of the inductor current, and the intensity of the magnetohydrodynamic processes of metal mixing decreases. To increase the efficiency of electromagnetic effect on the metal melt, it is necessary to supply the furnace with low-frequency currents at the stage of melting metal, and the power supply system must ensure the formation of high and low frequency currents [1, 2].

2. Induction furnace supply system

The power supply systems of modern induction smelting installations for metals are design on the basis of semiconductor frequency converters, usually consisting of a controlled rectifier and a self-commutated inverter. Functional diagram of the power supply system is shown on the Figure 1. It consists of a controlled rectifier (Rectifier) with a filter choke L_d in the DC circuit of a bridge current



inverter (Inverter), a block of compensating capacitors (Capacitor banks) connected in parallel with the induction crucible furnace (ICF).

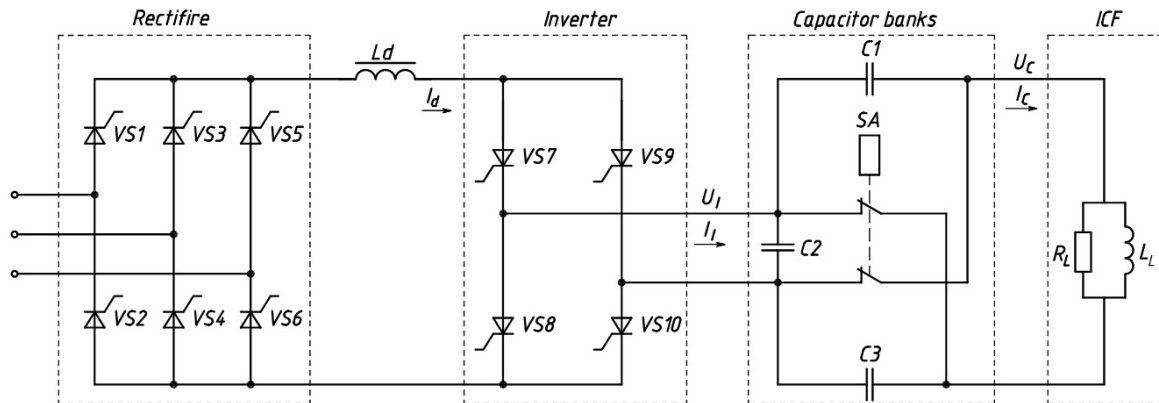


Figure 1. Functional diagram of the induction furnace power supply system

The capacitor block contains three series-connected groups of capacitors $C1$, $C2$, $C3$ and a switch SA . When SA in the closed position, all groups of capacitors are connected in parallel with the furnace inductor. The parallel load circuit formed by capacitors and inductor has its own phase change rate:

$$\omega_0 = 1 / \sqrt{L_{ind} \cdot C_C} = 1 / \sqrt{3 L_L \cdot C} \quad (1)$$

L_L – inductance of the furnace inductor;

$C_C = C1 + C2 + C3 = 3C$ – capacity of the capacitor banks.

With the synchronized control of the self-commutated current inverter valves by the voltage at the inverter output, its value can be determined from the ratio:

$$U_i = \frac{U_d}{0,9 \cdot \cos \beta} \quad (2)$$

U_d – average voltage of the rectifier;

β – angle of advancing the supply of control pulses to the inverter valves.

A rectangular form current with an amplitude equal to the average value of the rectifier current I_d and frequency f is formed at the inverter output, the fundamental harmonic of which can be determined by expanding it in a Fourier series.

$$I_i = 0,9 \cdot I_d \quad (3)$$

Active power at the inverter output is determined by the main harmonics of the output current and voltage:

$$P_i = I_i \cdot U_i \cos \beta \quad (4)$$

Based on the equality of active powers at the input and output of the inverter, assuming there is no loss in its elements $P_d = P_l$, the ratio between the active component of the load resistance R_L and the reduced resistance at DC inverter terminals R_d can be determined:

$$R_d = 0,81 \cdot R_L \cos^2 \beta \quad (5)$$

Therefore, the input current and input power are determined as:

$$I_d = U_d / R_d \quad (6)$$

$$P_d = U_d \cdot I_d \quad (7)$$

The switching stability of the inverter operation is ensured during the capacitive reaction of the load circuit, when the operating frequency of the inverter is greater than the resonant frequency of the load circuit $\omega > \omega_0$. In this case, a reverse voltage will be applied to the inverter valves after they are turned off for a time interval expressed in angular measure $\theta_r = \beta$. The time provided for recovery the inverter thyristor controllability can be set by tuning the inverter operating frequency from the resonant frequency of the load circuit:

$$\theta_r = \beta = \arctg \left[Q_L \left(q - \frac{1}{q} \right) \right] \quad (8)$$

$$Q_L = \frac{R_L}{\sqrt{L_L / C_L}} - \text{q-factor of the load circuit;}$$

$q = \omega / \omega_0$ – coefficient of the inverter operating frequency detuning from the load circuit resonant frequency.

The condition for the switching stability of the inverter during the capacitive reaction of the load circuit ($q > 1$) is the following inequality:

$$\theta_r = \omega \cdot t_q \quad (9)$$

t_q – turn-off time of the thyristor.

From the above equations, the ratio of the average value of the inverter input current I_d and the loop current I_c can be established:

$$I_c = 0,9 \cdot I_d \cdot \sqrt{1 + Q_L^2} \cdot \cos \beta \approx 0,9 \cdot I_d \cdot Q_L \cdot \cos \beta \quad (10)$$

Thus, we can conclude that the external characteristic of the current inverter in the self-excitation mode ($\beta = \text{const}$) is equivalent to the characteristic of the voltage source, in which when the active component of the inductor resistance R_L changes over a wide range, the output current I_l changes, and the output voltage U_l remains constant.

3. Characteristics of the power system

Let's consider the characteristics of the furnace power system in the *SA off* position. In this case, the groups of compensating capacitors are connected in series with respect to the furnace inductor and the total capacity of the compensating capacitor decreases and becomes equal to $C1 = C2 = C3 = C$.

$$C_{C.off} = \frac{1}{3}C \quad (11)$$

In this case, a nine-fold decrease in the compensating capacitor capacity occurs, and the resonant frequency of the load circuit increases:

$$\omega_{0.off} = 1 / \sqrt{L_L \cdot C_C} = \sqrt{3} / \sqrt{L_L \cdot C} \quad (12)$$

and it becomes three times higher than in the *SA on* position with a slightly changing inductance of the furnace inductor ($L_L \approx \text{const}$). Frequency ratio coefficient is the following:

$$K_f = \frac{\omega_{0.off}}{\omega_0} = \frac{\sqrt{3} / \sqrt{L_L \cdot C}}{1 / \sqrt{3L \cdot C}} = 3 \quad (13)$$

When changing the current frequency, the equivalent resistance of the furnace inductor $R_{L.off}$ can be determined from the relation:

$$R_{L.off} = R_L \cdot \left(\frac{\omega_{0.off}}{\omega_0} \right)^{n_1} \quad (14)$$

R_L – equivalent inductor resistance at low frequency;

$\omega_0, \omega_{0.off}$ – resonant frequencies of the load circuit in the first and second *SA* position;

$n_1 = 1,35 \div 1,4$ – index for crucible furnaces [1].

If $n_1 = 1,35$, then $R_{L.off} = 4,41 \cdot R_L$.

The inductance of the inductor insignificantly depends on the current frequency and the reactance of the inductor increases and is determined as:

$$X_{L.off} = X_L \cdot \left(\frac{\omega_{0.off}}{\omega_0} \right)^{n_2} \quad (15)$$

$n_1 = 0,8 \div 0,95$ – index for melting furnaces [1].

If $n_1 = 0,9$, then $X_{L.off} = 2,7 \cdot X_L$.

The q-factor of the furnace inductor is determined by the ratio of active and reactive resistance:

$$Q_L = \frac{R_L}{X_L} \quad (16)$$

When switching from one operating mode to another, the q-factor of the furnace inductor and load circuit change. The multiplicity of increasing the q-factor of the load is defined as:

$$Q_{L.off} = \frac{R_{L.off}}{X_{L.off}} = 1,63 \cdot Q_L \quad (17)$$

The compensating capacitor consists of three series-connected capacitors, one of which (C2) is connected to the inverter output. Such kind of connection of the inverter capacitors and the load represents a capacitive voltage divider, the transmission coefficient of which at a sufficiently high q-factor of the load circuit is determined as:

$$K_U = \frac{U_{C.off}}{U_I} = 1 + \frac{C_2}{C_S} = 1 + \frac{C}{C/2} = 3 \quad (18)$$

$$C_S = \frac{C_1 \cdot C_3}{C_1 + C_2} = \frac{C}{2} \text{ – capacity of the serial leg of the voltage divider;}$$

$$C_2 = C \text{ – capacity of the voltage divider parallel leg.}$$

When switching SA, if the voltage at the inverter output U_I remains unchanged ($\beta = const$), then the voltage at the inductor changes three times ($K_U = 3$), therefore, the change in the active power of the furnace can be determined by the coefficient of increase in active power:

$$K_P = \frac{P_{L.off}}{P_L} = \frac{U_{C.off}^2 / R_{L.off}}{U_C^2 / R_L} = \frac{(3U_C)^2 / (4,41R_L)}{U_C^2 / R_L} = 2 \quad (19)$$

$$U_{C.off} = K_U \cdot U_L \text{ – voltage at the inductor;}$$

$$U_C = U_I \text{ – voltage at the output of inverter.}$$

The magnitude of the current in the inductor is determined as:

$$I_{C.off} = \frac{U_{C.off}}{Z_{L.off}} \quad (20)$$

$$U_{C.off} = K_U \cdot U_I \text{ – voltage at the inductor at the operating frequency } \omega_{off} = 3\omega;$$

$Z_{L.off}$ – resistance of the load circuit at a frequency ω_a .

Based on the above relations determine $Z_{L.off}$:

$$Z_{L.off} = \frac{R_{L.off}}{\sqrt{1 + Q_{L.off}^2}} = 2,7 \frac{R_L}{Q_L} = 3,33 \frac{R_d}{Q_L \cdot \cos^2 \beta} \quad (21)$$

Then $I_{C.off} = 0,333 \cdot K_U \cdot Q_L \cdot I_d \cdot \cos \beta = I_d \cdot Q_L \cdot \cos \beta$.

Determine the rate of change of current when switching SA:

$$K_I = \frac{I_{C.off}}{I_C} = \frac{I_d \cdot Q_L \cdot \cos \beta}{0,9 \cdot I_d \cdot Q_L \cdot \cos \beta} = 1,11 \quad (22)$$

Thus, when switching the power supply mode of the furnace, the magnitude of the inductor current changes insignificantly, while its frequency changes in 3 times. However, active power at a low frequency is halved.

4. Calculation of power system parameters

Consider the calculation of the dual-frequency power system parameters for an induction crucible for melting cast iron with a capacity of $V = 400$ kg. Calculation of the furnace parameters was carried out according to the method of computer simulation given in [3]. With a supply voltage of $U = 380$ V and an operating frequency of the furnace inductor current in the metal melting mode (SA - turn-off)

$f_H = 1000$ Hz, the furnace parameters and the electrical load characteristics of the power supply system are given in table 1. The power supply system parameters in the mixing mode of the metal at a low operating frequency of $f_L = 325$ Hz (SA - turn-on) are also given there. According to the calculation data, the capacitance of the compensating device capacitors of

$C_c = 3C$; $C = \frac{C_c}{3} = \frac{1223}{3} = 408$ μF can be determined and their type selected.

Table 1. Electrical parameters of the power supply system and load.

Electric parameters of the furnace inductor		
The operating frequency of the inductor current, Hz	1000	325
The turns number of the furnace inductor	30	
The reduced resistance of the inductor, Ohm	13	2,15
Inductor reactance, Ohm	1,2	0,419
Power factor inductor, $\cos \varphi_L$	0,093	0,148
Inductor impedance Z_L , Ohm	1,206	0,424
Electric efficiency of inductor	0,799	0,795
Power system parameters		
Inverter control angle β	30	25

Inverter output voltage U_L , V	700	650
Inverter output voltage U_c , V	2000	650
Active power of the furnace P_L , kW	310	148
Reactive power of capacitors Q_c , kVar	3445	1041
Inductor current I_c , A	1660	1535
Switch current I_{st} , A	-	1013
Compensating Capacitance C_c , μ F	136	1223
Capacitor Voltage	700	650

According to the calculation data, it is seen that when switching from the metal melting mode to the mixing mode, the power consumed by the load decreases, and the current in the inductor changes slightly.

When switching the operating mode, the inductor parameters change in approximately the same proportions that were determined by the formulas (14, 15):

$$\frac{R_{L.off}}{R_L} = \frac{13}{2,85} = 4,56; \quad \frac{X_{L.off}}{X_L} = \frac{1,2}{0,419} = 2,86$$

Thus, the proposed method for calculating the parameters of a dual-frequency power supply system for induction crucible furnaces can be used with sufficient accuracy in engineering calculations.

5. Conclusion

According to the results of the study, it can be concluded that the proposed power supply system is advisable to use in high-frequency operation mode for forced heating and metal melting, and the low-frequency operation mode is necessary during technological operations when efficient metal mixing is ensured.

Also, authors in researches [4, 5, 6,7] proved that dual-frequency power supply provide an increase in the rate of the molten metal motion in the case of melting, and also allows the processing of parts with a complex geometric shape of the surface in case of heating.

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